

"Innervated" Pipelines: A New Technology Platform for In-Situ Repair and Embedded Intelligence

PI:

Dr. Paul Ohodnicki, University of Pittsburgh (Pitt)

Team Members / Co-Pls:

Dr. Kevin Chen, Dr. Jung-Kun Lee, University of Pittsburgh (Pitt) Mr. Glenn Grant, Dr. Kayte Denslow, Mr. Christopher Smith, Pacific Northwest National Laboratory (PNNL)

Project Vision

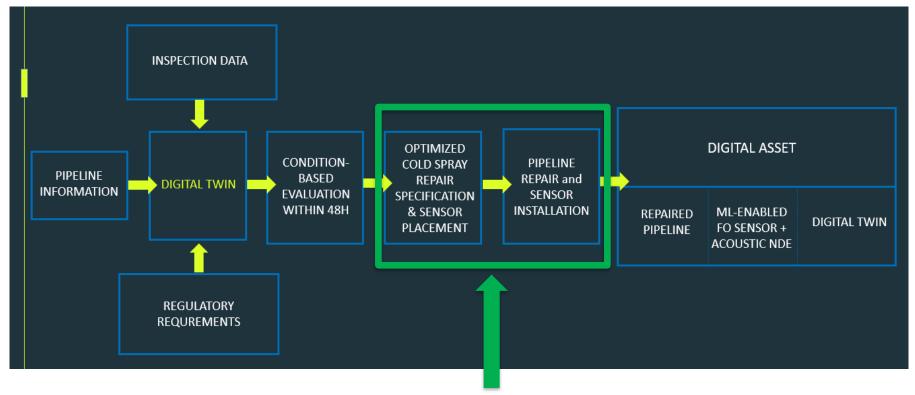
Demonstrating in-situ repair and fiber optic sensor deployment through robotic deployable cold-spray, combined with a fusion of acoustic NDE and distributed fiber optic sensing in an artificial intelligence-based classification and diagnostic framework for asset health monitoring.

Total Project Cost: \$1.0M
Length 12 mo.

The Concept: Big Picture

"Innervated" Pipelines of the Future

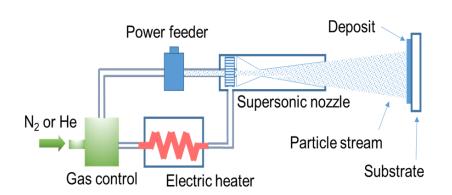
In-Situ Repair + Embedded Intelligence + Digital Asset Modeling



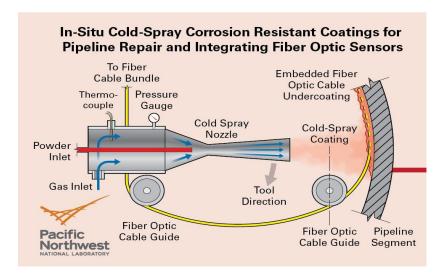
Focus of Initial 12-Month Project Efforts: Targeted Feasibility Demonstrations
(1) Cold Spray Repair Methodology, (2) Fiber Optic Embedding, and (3) Fiber Optic Installation

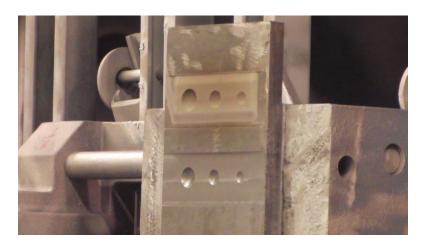


Cold Spray Based Repair + Sensor Embedding



- Cold-spray process: Cold spray is a proven highrate metal deposition process where metal powders (~5-45 µm particles) are combined with hot gas, accelerated to high velocity (Mach 1-4) and deposited on repair area to build up thickness
- Fully dense, thick metal deposit, metallugically bonded to substrate
- Can repair through-holes and "build back" corrosion allowance
- Can embed sensors in the wall for condition assessment







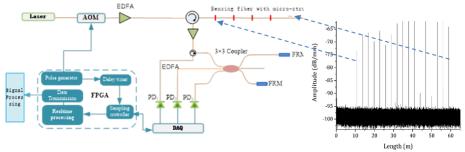
The concept is to make a pipe-in-a-pipe that may offer structural credits far superior to polymer liner options

Advanced Acoustic NDE / Optical Fiber Methods





Custom Developed, Low-Cost Distributed Fiber Optic Sensors and Interrogators



Physics Based Models

Reduced Order

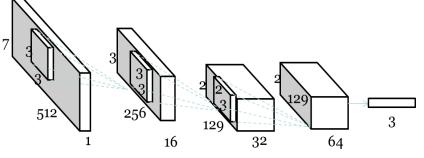
Modeling

Experiments on

Representative Systems

Acoustic NDE Guided Wave Interrogation

(Controlled Acoustic Source) + Distributed Fiber Optic Sensing



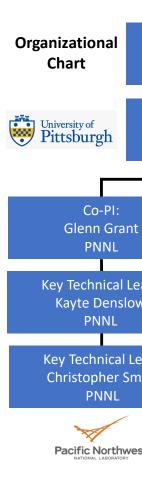
Al-Based Classification of Acoustic Data



The concept combines acoustic NDE and fiber optic sensing with Al-classification frameworks for real-time monitoring.

The Team: Overall Project Structure

Project Organizational Chart for Year 1 Efforts



ARPA-E Program Management

Project PI: Prof. Paul Ohodnicki University of Pittsburgh University of Pittsburgh

Industry Advisory Committee

Prof. Paul Ohodnicki (PI) Associate Professor Mechanical Eng. & Materials Science

Electrical and Computer Eng.



Key Technical Lead: **Kayte Denslow**

Key Technical Lead: Christopher Smith



Co-PI: Prof. Kevin Chen University of Pittsburgh

Key Technical Lead: Prof. Jung-Kun Lee University of Pittsburgh

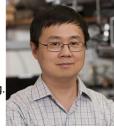
Dolendra Karki Senior Research Associate University of Pittsburgh

Graduate Students (2) University of Pittsburgh

University of

Prof. Kevin Chen (Co-PI) Professor

Electrical and Computer Eng.



Prof. Jung-Kun Lee (Co-PI) Professor Mech. Eng. & Mat. Sci.





Mr. Glenn Grant (Co-PI) Chief Scientist

App. Mat. and Manufacturing Group Energy and Environ. Directorate



Dr. Kayte Denslow

Pittsburgh Research Focus: Non-Destructive Evaluation, Novel Transducers, Acoustic Guided Wave Mode Propagation



Mr. Christopher Smith

Research Focus: Cold Spray, Solid Phase Joining and Processing (Friction Stir Welding), Leads projects in Robotic platform integration



Project Objectives Primary Focus in First Year Efforts

- Key Innovations to Be Pursued in year 1
 - Cold-spray in-situ repair concept
- Primary Risks to Be Mitigated in year 1
 - Basic feasibility of cold spray repair
 - Feedstock material (cost, performance)
 - Coating quality (thickness, uniformity, permeability)
 - Deployment scenario scoping (industry advisory group)
 - Economic models of initial deployment scenarios
- Key Innovations to Be Pursued in year 1
 - Internally deployed distributed fiber optics
 - Multiphysics modeling for acoustic signatures of defects
- Primary Risks to Be Mitigated in year 1
 - Protection of fibers for internal deployment
 - Need for large data sets to train AI / ML models



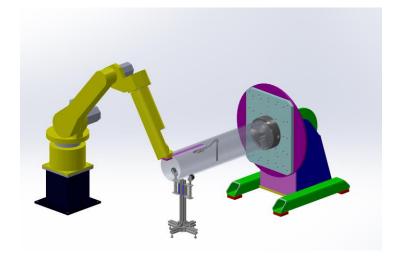




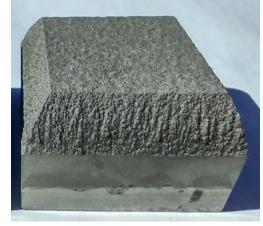
Results: Cold Spray Process Demonstrations

Successful Coating Development: Validation Trials

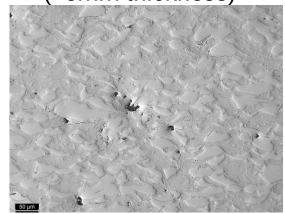
- Down-selected 430L SS in Q1-Q2
- Additional Powder Approaches Explored
 - Duplex Stainless Steel
 - Aluminum
- Coatings of >5mm Thickness Achieved (Major Milestone Successfully Completed)



Preparing for In-Pipe Demonstrations



Duplex Stainless Steel Coating (>5mm thickness)



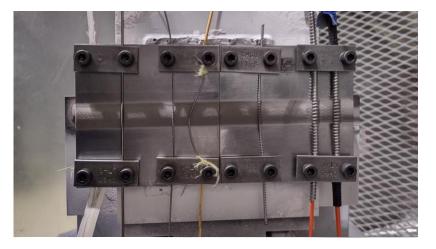
Porosity < 1%, Adhesion >10ksi



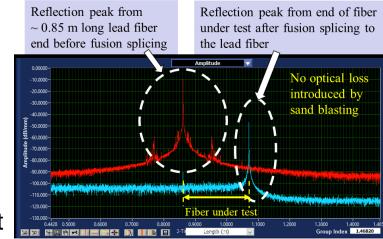
Results: Fiber Optic Sensor Embedding

Initial Cold-Spray Embedding Tests Highlighted Path Forward

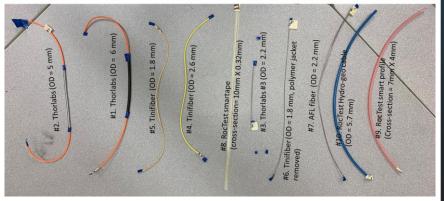
- Initial Trials of Cold-Spray Embedding
- Commercial Packaging Options Explored
 - Polymer-Based
 - Metallic Tubing-Based
 - Hybrid Approaches
- Metal Packaging Superior, Fixturing Important



Initial Embedding Trials : More Planned



Initial Package Benchmarking



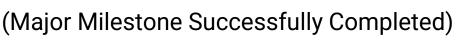
Commercial Packaging Options

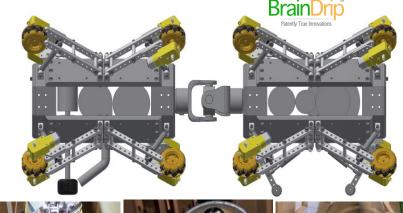


Results: Fiber Optic Deployment Tool (FODT)

Successful Demonstration of 1st Generation FODT

- Self-Propelled, Remote Controlled
- Self- Contained Material Storage
- Mechanized Feed Systems
- Application Path Abrading and Air Blow Off







8" Diameter Fiber Optic Deployment Tool Demo #1









Patent Filed in Q3 2021



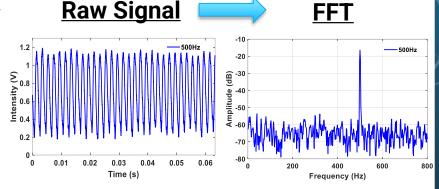
8" Diameter Fiber Optic Deployment Tool Demo #2 50 Foot Long Pipe Segment

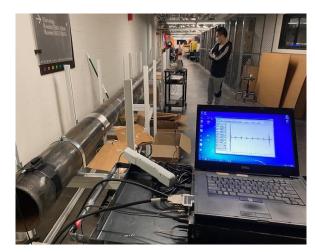
Results: Fusion of Fiber Optics + Acoustic NDE

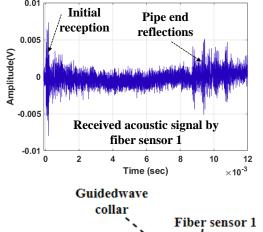
Successful Demo of Fiber Optics + Guided Acoustic NDE

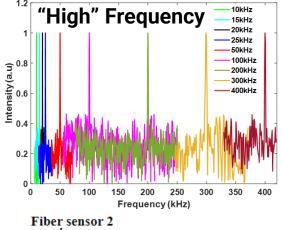
- Existing Fiber Sensing Limited in Frequency
- Ultrasonic Guided NDE Operates @ 20kHz+
- New Fiber Technology for up to 400kHz
- Successful 30kHz Guided Waves Measured

(Major Milestone Successfully Completed)









Fiber sensor 1

Fiber sensor 2

Steel pipe, OD: 8 inch, length: 15 m

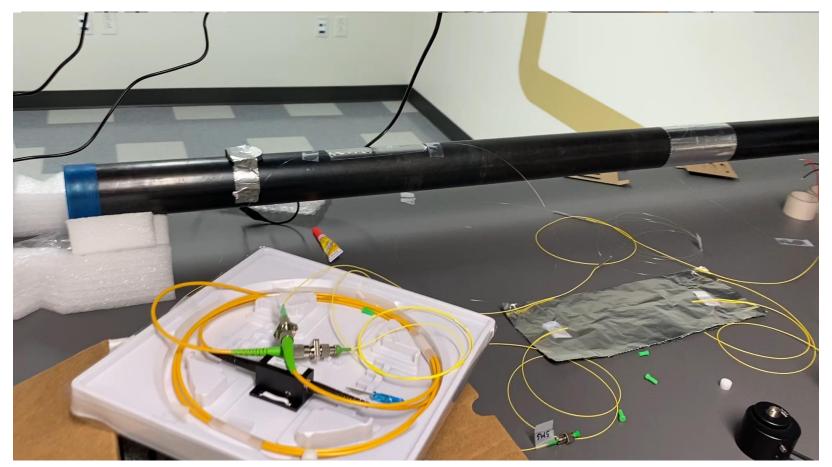
30kHz Ultrasonic Guided Wave Demo

Disclosure Filed in Q4 2021



Results: Fusion of Fiber Optics + Acoustic NDE

Successful Development of New Acoustic Fiber Optic Sensing



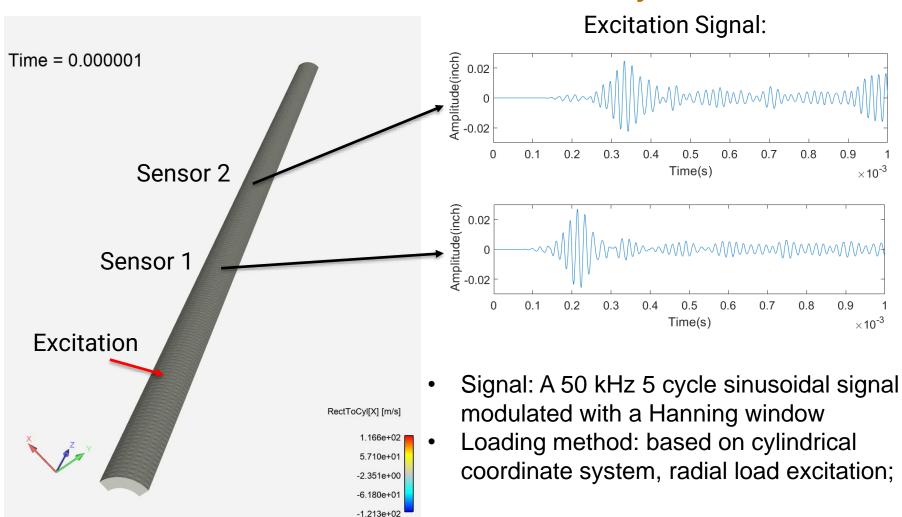
Disclosure Filed in Q4 2021

2" Pipe Piezoelectric Collar Demo



Results: AI-Enhanced Fiber Optic Sensing

Successful Demo of AI-Classification with Physics Models

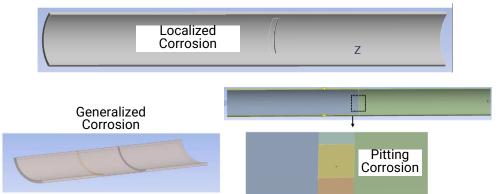




Results: AI-Enhanced Fiber Optic Sensing

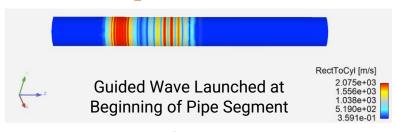
Successful Demo of AI-Classification with Physics Models

- Established Accurate Physics-Based Models
- Simulated Simulations for Various Defects
- Trained a Neural Network (AI) Framework
- Successful Validation of Training Accuracy

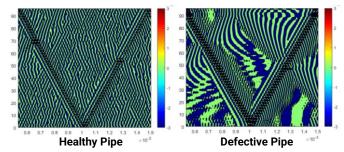


Variations of Size and Type → Integrated in Classification Framework

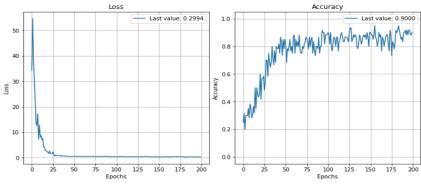
Classification of Corrosion Defects



Simulated Responses



AI Classification Framework





Challenges and Risks

Challenge = Cold Spray Full Repair Deployment

- Optimization of process parameters for cold-spray repair
- Development of robotic deployment strategies

Risk Mitigation

Industry Advisor Group Engagement During Initial Feasibility
 Demonstrations of Year 1 to Inform Deployment Scenarios

Industry Advisory Committee





Mat Podskarbi







Ruishu Wright

Kent Weisenberg



Several Strategies Developed and Assessed

Challenges and Risks

- 2nd Meeting of Industry Advisory Group
 - Scoping of various deployment scenarios
 - Include economic, technical, and regulatory considerations
 - Developed several scenarios for consideration
- 1) Full Remote Cold-Spray Repair = Highest Value → Deployment Risks
- 2) Selective Cold-Spray Repair = High Value → Reduced Risks
- 3) Alternative Proposed to ARPA-E = Hybrid Liner / Cold-Spray

Integrated Fiber Optics is of Significant Value in Any Scenario
Industry Advisory Committee





Mat Podskarbi







Kent Weisenberg

Ruishu Wright



Several Strategies Developed and Assessed

Potential Partnerships

- Potential to Enhance Project Outcomes / Impacts Including:
 - Identifying high priority defects and failure modes for physics-based simulations of acoustic signatures
 - Opportunities for integration and field validation of fiber optic sensor technology, including in-pipe integration
 - Adopting deployment strategies from other technologies



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Dr. Glenn Grant Glenn.grant@pnnl.gov



Summary Slide

Technology Summary

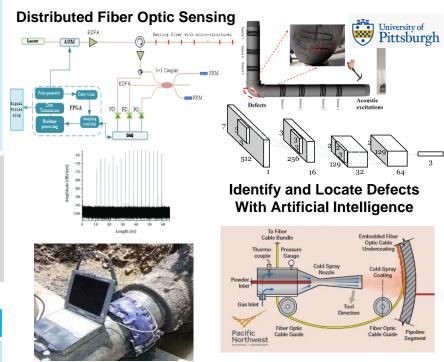
- In-Situ Pipeline Repair, Coating, and Sensor Embedding Through Robotically Deployed Cold-Spray Methods
- Fiber Optic Sensing and Commercial NDE Technique Synergy with Artificial Intelligence Data Analytics for Defect Identification and Localization

Technology Impact

- Unprecedented Capability for In-Situ Repair and Sensor Embedding at Scale for an Economical Cost
- New "Embedded Intelligence" Imparted By Real-Time Monitoring and an AI Classification System Approach

Proposed Targets

Metric	State of the Art	Proposed
Deployed Fiber Optic Sensor Cost Per km	>\$5000 / km, external to pipe	< \$500 / km, internal to pipe
Deployed Internal Coating Cost	Does Not Exist	< \$500 / m



Guided Wave

Acoustic NDE

- In-Situ Repair, Coating and **Sensor Embedding with Robotic Deployable Cold-Spray**
- Proposed Year 2/3 Efforts Would Target:
 - Deployment of Pipe-In-Pipe Repair and Fiber Optic Sensing
 - Development of AI-Framework for NDE and Fiber Optics

Extra Slides Follow



Project Objectives: First Year Project Timeline

Q1 Q2 Q3 **Project Management / T2M** 3-Month No Cost Extension **Industry Advisory COVID** (Feedstock Delays) **Group Meeting Industry Advisory** First Completed First Iteration of **Group Meeting** Draft T2M Plan T2M Plan **Cold-Spray Process Development and Validation** Robotic Deployment Go/No-Go: **Tool Modification** Robotic **Initial Coating Deployment Tool** Validation Experiments **Coating Validation** Modification **Experiments** Fiber Optic Sensor Deployment, Embedding, and Acoustic Modeling Fiber Optic Sensor **Embedding with** Fiber Optic Cold Spray Interrogation Completed Fiber with Acoustic **Optic Robotic Excitation**

Deployment Tool

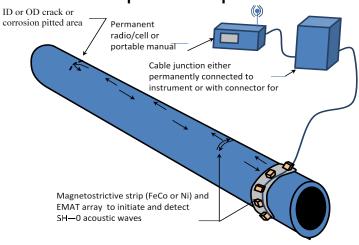
Design



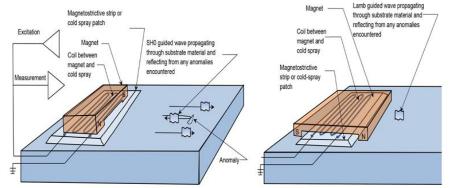
Advanced Acoustic NDE Methods

Acoustic NDE is a Mature, Regulatory Approved Technique for Pipeline Monitoring





Cold-Spray Electromagnetic Transducers



Propose New Cold-Spray Fabricated Ultrasonic Transducers and Advanced NDE Interrogation Techniques and Data Analysis.



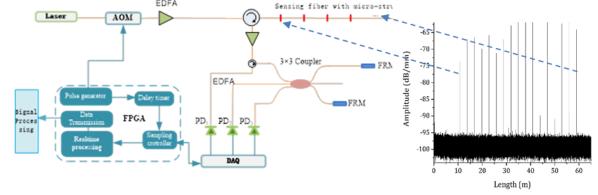
Distributed Optical Fiber Sensing

External Deployed Fiber Optic Sensors are Commercially Available



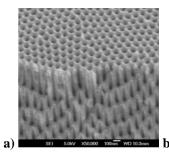
University of Pittsburgh

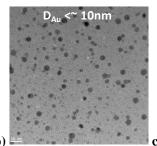
Custom Developed, Low-Cost Distributed Fiber Optic Sensors and Interrogators

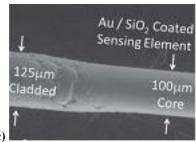


Fiber Optic Coatings for Protection / Corrosion Sensing







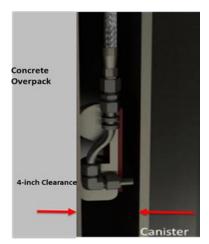


Propose New Internal Deployed, Low-Cost Cold-Spray Embedded Fiber Optics and Functionalization for Corrosion Monitoring.



Advantages of Cold-Spray Repair Method

- Lower temperature process compared to conventional repair techniques (e.g., welding), and method of application results in reduced thermal input to area of repair
 - No heat affected zone (HAZ) that alters the microstructure of the base metal as occurs with traditional fusion-based welding operations
 - No need for post-repair stress relieving
 - No ignition hazard from flame, required pre-grinding operations, or other operations consisting of spark-generating moving parts
- Can achieve high deposition rates, on the order of 350 g/min
- No restrictions on repair thickness
- Can apply (i.e., bond) dissimilar metals
- Can be adapted to a robotic platform







Corroded Reduction Gearbox Housing



Cold Spray Repaired Reduction Gearbox Housing



Images Credit to VRC Metal Systems



The Team : People and Capabilities



Prof. Paul Ohodnicki (PI)

Associate Professor

Mechanical Eng. & Materials Science

Electrical and Computer Eng.



Project Capabilities and Responsibilities

Project Leadership and Coordination Tech 2 Market Plan Fiber Optic Sensor Technology Physics-Based Al-framework Training Corrosion Sensor Technology

Prof. Kevin Chen (Co-PI)

Professor

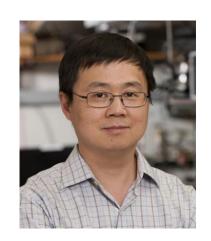
Electrical and Computer Eng.

Fiber Optic Sensors

Photonics

Distributed Interrogation

Al / Sensor Fusion

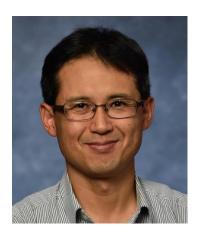


Prof. Jung-Kun Lee (Co-PI)

Professor

Mech. Eng. & Materials Science

Functional Materials
Thin Film Coating (ALD)

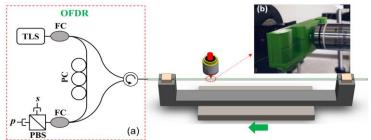




The Team: Laboratory Facilities



Fiber Optics Facilities

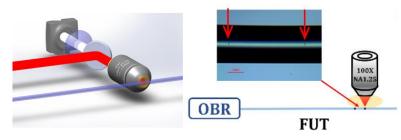




Thin Film Coating / ALD Facilities



Atomic Layer Deposition, Sputtering / Evaporation, Wet Chemistry



Distributed Interrogation Systems, Ultrafast fs-laser Processing, Photonics and Microwave Instrumentation



Structural / Metallurgical Facilities





Structural Characterization (SEM, TEM, XRD), Metallurgical Testing

The Team : People and Capabilities



Mr. Glenn Grant (Co-PI)
Chief Scientist
Applied Materials and
Manufacturing Group
Energy and Environment
Directorate



Project Capabilities and Responsibilities

Cold-Spray Coating Technology Cold-Spray Coating Deployment Coating Materials Corrosion Protection Fiber Optic Sensor Embedding Non-destructive Evaluation (NDE)

Research Focus: Advanced manufacturing, forming, joining, thermomechanical processing. Leads programs in Solid Phase Processing

Dr. Kayte Denslow

Research Focus: Non-Destructive Evaluation, Novel Transducers, Acoustic Guided Wave Mode Propagation



Mr. Christopher Smith

Research Focus: Cold Spray, Solid Phase Joining and Processing (Friction Stir Welding), Leads projects in Robotic platform integration

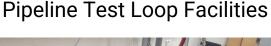


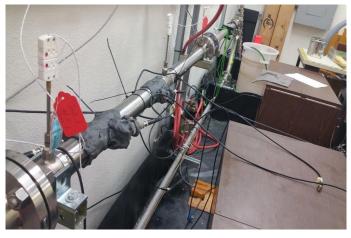


The Team : Laboratory Facilities









NDE / EMAT Facilities Summary



Cold Spray Facility Summary

- VRC GEN 3 High Velocity System
- Applicator end effector nozzle on stationary robot platform
- Rotary Positioning System

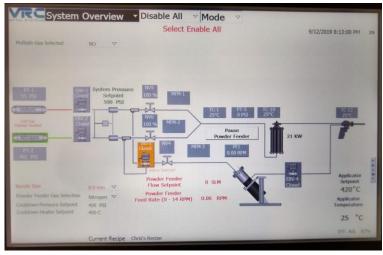




Cold Spray Setup and Process Parameters

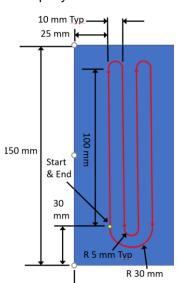
- Metal powder
 - Material
 - Density
 - Particle size and shape
 - Particle size distribution (PSD)
 - Hardness
- Cold spray process input parameters
 - Carrier gas (He or N₂)
 - Carrier gas temperature at entrance to nozzle
 - Carrier gas pressure
 - Powder feeder speed
 - Powder feed gas flow rate
 - Cold spray gun orientation
 - Nozzle standoff distance
- Nozzle
 - Geometry
 - Material
 - Application gun (VRC "Barrel Applicator")





VRC Systems Cold Spray HMI

- Substrate
 - Surface preparation
 - ✓ Cleaning
 - ✓ Texture
 - ✓ Bonding coat
 - Temperature
- Raster Pattern
 - Path
 - Step-over distance / spray overlap
 - Number of layers
 - Robot travel speed



IR No.: PNNL-SA-150003

Results:

Prior VRC Metal Systems Repair Demonstrations

Stopping Active Pressurized Leaks (1000psi)











Small ID Corrosion Repairs



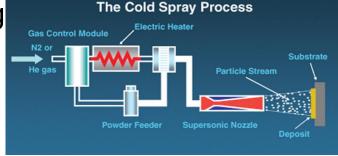
Portability of Cold Spray (Hand Operated and Robotic)





Project Objectives Cold-Spray In-Situ Repair

- Selection and sourcing of feedstock materials
 - Emphasis on low-cost steel and iron feedstock (cost)
 - Quality in terms of size, uniformity, required heat treatment
 - Early process feasibility and screening
- Coating validation experiments
 - Bare steel and/or cast-iron coupons
 - Target thicknesses > 5mm, coating density >95%, Adhesion
 >7000psi as per ASTM C633 (Positest Adhesion testing)
- Robotic deployment tool validation
 - Establish a rotational head spray nozzle to coat pipe interior
 - Successfully coat a 10-24" diameter pipe, 4ft long, 5mm thick
 - Acoustic NDE benchmarking of coating quality
 - Transition Technology to Industry Partners in Future Years

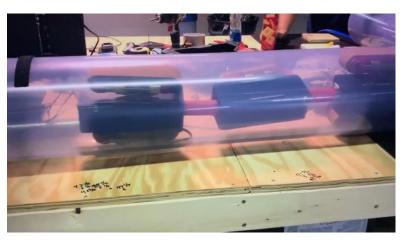




Project Objectives Fiber Optic Sensor Technology

- Fiber optic sensor embedding using cold spray
 - Trials of fiber optic embedding in cold spray > 3mm thick
 - Measure transmission / backscattering of embedded fibers
 - Explore coatings and protections for fiber optic sensors
- Fiber optic robotic deployment tool design and demonstration
 - Internal pipe installation on bare steel or cast-iron
 - Scaled down automated deployment tool design and demo

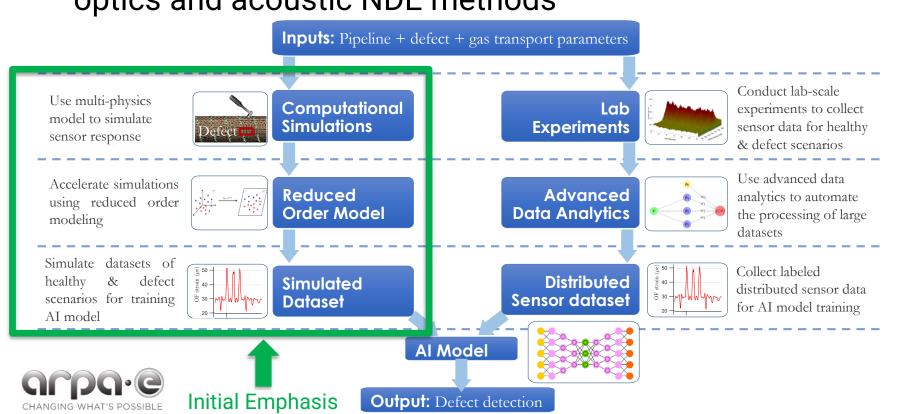






Project Objectives Physics Based Modeling of Defect Signatures

- Establish representative pipeline segment models
 - Acoustic, temperature, and strain distribution defect free
 - Characteristic distributions for representative defects
 - Sampling of expected sensing signatures for both fiber optics and acoustic NDE methods



Project Objectives Technology to Market

- Establishment and Meeting of Industry Advisory Group
 - Assess cold-spray coating and optical fiber embedding
 - Economic assessment
 - Regulatory considerations
 - Scoping of various deployment scenarios
- Draft / first completed technology to market plan

Industry Advisory Committee





Mat Podskarbi







Kent Weisenberg

Ruishu Wright

